The Coulomb Anomaly in Strongly Disordered Films*

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Electron tunneling measurements of the Coulomb anomaly in the density of states in strongly disordered quench condensed granular films are presented. The strength of this anomaly grows with increasing sheet resistance, R_N, at low R_N but saturates at high R_N. We suggest that the granular morphology of these films is responsible for the saturation.

1. INTRODUCTION

Increases in the static disorder in metal films degrades the screening capabilities of the conduction e^-, increases spatial correlations among them and thus, increases the effective $e^- - e^-$ interactions. This leads to a decrease of the density of states about E_F. [1 – 3] In two dimensional weakly disordered systems, this decrease is given by [4]:

$$\frac{\delta N(E)}{N_0} = \lambda_\mu ln(\frac{l}{\xi}) ln(\frac{|E - E_F|\tau_{el}}{\hbar}) \quad (1)$$

where λ_μ depends on the strength and form of the effective $e^- - e^-$ interactions, l is the mean free path, ξ is the localization length and τ_{el}^{-1} is the rate of elastic collisions. This density of states anomaly appears as an anomaly in the conductance as a function of voltage, $G_j(V)$ of tunnel junctions with a disordered film as one of the electrodes. Here, we present preliminary studies of this anomaly in films that range from the weakly disordered limit, where this theory applies, to the strongly disordered limit, where it does not. We find that film morphology plays an important role in determing the strength of this anomaly and thus, the strength of the $e^- - e^-$ interactions in strongly disordered films.

2. SAMPLES

The disordered films were deposited onto cooled substrates ($\sim 8K$) on which an oxidized Al strip had been previously deposited. The disordered film and Al strip served as the tunnel junction electrodes. Four terminal measurements of $G_j(V)$ were performed at 8K in situ. In fact the normal state conductance $G_j(V)$ does not depend on temperature for $eV > kT$. We have measured $G_j(V)$ of granular Pb and Sn films with R_N ranging from 10Ω ($k_F l \gtrsim 1$) up to $70k\Omega$ ($k_F l \sim .04$).

$G_j(V)$ can be written

$$G_j(V) = \int_{-\infty}^{\infty} N_{Al} N_{Film} \frac{\partial f(E + eV)}{\partial (eV)} P(E) dF$$

where E is the energy relative to E_F, f is the Fermi distribution, V is the voltage across junction, N_{Al} is the density of states for the Al strip and N_{Film} is the density of states for the investigated film. P(E) is the tunneling probability. We normalized all curves by the lowest R_N film for each experimental run to eliminate the effects of N_{Al} and P(E), so the normalized junction conductance, G_N, reveals corrections to N_{Film} due to disorder effects.

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3. RESULTS

In Fig. 1 we show $G_N(V)$ vs. $\ell n(V)$ for a series of granular Sn films. The dotted lines are data and the solid lines show linear regions. These regions shrink and their slopes grow with increasing R_N. The functional form of $G_N(V)$ at high voltages is unclear.

We plot the slope vs. R_N for Pb and Sn films in Fig. 2. At low R_N these slopes grow, but at high R_N they saturate. The sheet resistance at which they saturate, R_N^*, and the saturation value are both higher in Sn than in Pb. This saturation value appears to scale with the inverse of the film thickness.

According to Eq.(1) the slope of this $\ell n(V)$ dependence corresponds to the strength of the $e^- - e^-$ interactions and R_N represents the degree of the disorder. Disorder enhances the effective $e^- - e^-$ interactions, so the slopes should grow with increasing R_N. We believe that this observed saturation results from a morphology change ("granular" to "uniform") that occurs near R_N^*. Above R_N^*, films are made of isolated grains and the transport properties are dominated by intergrain tunneling processes. Below R_N^*, the grains start to couple together and the film becomes more uniform. For the granular morphology the effective $e^- - e^-$ interactions are dominated by grain charging effects. These depend only on the intergrain capacitances which are independent of R_N. For the uniform morphology, where the theory applies, the effective interactions depend on R_N.

4. SUMMARY

We have measured the density of states of granular Pb and Sn films with R_N up to $70k\Omega$. The strength of the coulomb anomaly saturates at high R_N. We attribute this effect to the granular morphology of the films.

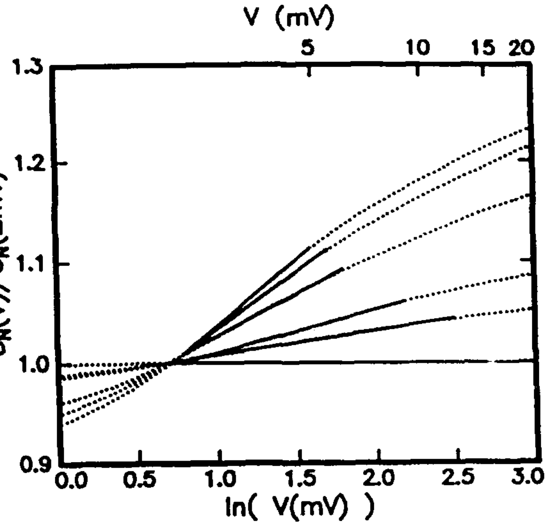

Fig. 1 granular Sn $30\Omega \leq R_N \leq 70k\Omega$

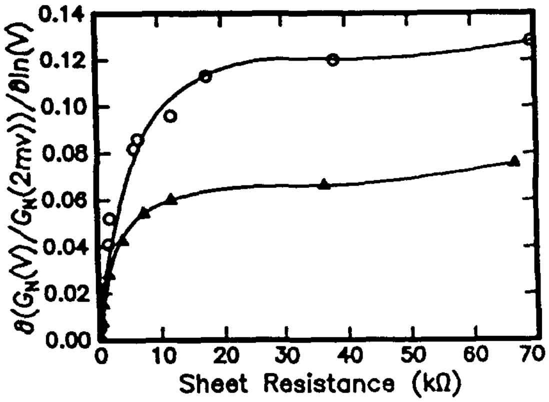

Fig. 2 O:Sn Δ:Pb

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1. "Electron Tunneling Determination of the Order-Parameter Amplitude at the Superconductor-Insulator Transition in 2D," by J.M. Valles, Jr., R.C. Dynes, and J.P. Garno, *Phys. Rev. Lett.* **69**, 3567 (1992).
2. "Perpendicular Upper Critical Field of Granular Pb Films Near the Superconductor-to-Insulator Transition," by Shih-Ying Hsu and J.M. Valles, Jr., *Phys. Rev.* **B47**, 334 (1993).
3. "Magnetic-Field-Induced Pair-Breaking Effects in Granular Pb Films Near the Superconductor-to-Insulator Transition," by Shih- Ying Hsu and J.M. Valles, Jr., *Phys. Rev.* **B48**, 4164 (1993).
4. "The Proximity Effect in Ultrathin Granular Pb Films," by Shih-Ying Hsu, J.M. Valles, Jr., P.W. Adams, and R.C. Dynes, to be published in the Proceedings of LT20.
5. "The Coulomb Anomaly in Strongly Disordered Films," Shih-Ying Hsu and J.M. Valles, Jr., to be published in the Proceedings of LT20.